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Blood Oxygenation. I. The Kolff Apparatus. II. Multiple Horizontal Rotating Cylinders.*

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I. The Kolff Apparatus. In the course of construction of a perfusion apparatus capable of maintaining the circulation of an entire animal, an attempt has been made to use a method of oxygenation without an open blood-oxygen interface.

Experimental. Cellulose sausage casing was wound spirally around a horizontal revolving drum 50 cm in diameter and 50 cm long in a fashion similar to that of Kolff.¹ Casing of the following sizes was utilized: diam. 1.84 cm with 0.203 mm wall thickness, diam. 2.40 cm with 0.203 mm wall thickness,

and diam. 4.16 cm with 0.406 mm wall thickness. The diffusion area was approximately 10,000 cm². An atmosphere of 95% O₂ and 5% CO₂ was maintained around the casing. Whipped beef blood at 37°C was introduced from a reservoir at one end of the spiral casing and collected at the other end. While the blood flowed through the casing, the drum was revolved at speeds varying between 17 and 100 r.p.m. Blood samples before and after passage through the apparatus were analyzed for oxygen content by the method of Van Slyke.² In some experiments the casing dipped into Ringer-Locke solutions to keep it wet. In order to utilize the mixing qualities as well as the diffusion surfaces of the spiral casing, small bubbles of oxygen were in-

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¹ Kolff, W. J., *The Artificial Kidney*, J. H. Kok, N.V. Hampen (Holland) 1946.

² Van Slyke, D. D., and Neill, J. M., *J. Biol. Chem.*, 1924, **61**, 523.

KOLFF APPARATUS. MULTIPLE ROTATING CYLINDERS

TABLE I.
Comparison of Oxygenators.

	Kolff	Kolff with O ₂ inj. into blood*	Horizontal cylinder
cc O ₂ introduced into blood per min.			
Avg	5.87		20
Max.	9.73	44	24.3
Avg vol. content, cc	200	360	70
cc O ₂ /min. per cc blood			
Avg	.0299		.314
Max.	.0487	.122	.406
Avg blood flow, cc/min.	150	550	250

* One experiment was done to determine the maximum oxygenation obtainable under existing conditions by this method.

roduced through a 25 gauge hypodermic needle into the blood stream as it entered the apparatus. In order to obtain a significant increase in oxygenation at least 0.5 liter of O₂ per minute had to be injected into the blood.

Results. It was found that a maximum of 9.73 cc of O₂/min. could be introduced into the blood. The blood content of the casing was 200 cc at a flow rate of 150 cc/min. Thus, a maximum of 0.0487 cc of O₂ was introduced into the blood per minute per cc of blood in the apparatus. Keeping the casing wet did not increase the oxygen uptake. Introducing bubbles of oxygen directly into the blood stream negated the theoretical advantage of no open blood-oxygen interface which this apparatus presented, and foaming resulted. At a blood flow of 550 cc/min., 44 cc of O₂ per minute was introduced into the blood per cc of blood in the casing, but 14 cc of blood was lost as foam per minute.

II. Multiple Horizontal Cylinders. Considering that foaming and hemolysis in an oxygenator are partly due to rapid relative motion between the blood and a surface, a slowly revolving cylinder was used upon which to film the blood.

Experimental. A metal cylinder 56 cm long and 17 cm in diameter was mounted on rollers nearly horizontally, the angle being varied from 5° to 20°. Inside this cylinder, another cylinder of approximately 12.5 cm diameter was laid. A variety of cylinders 12.5 cm diameter was used, made of fine wire

screen or thin acetate plastic. The plastic cylinders were perforated by numerous holes of varying size or by rectangular openings, attempting to arrive at a design which would allow blood to film on their inner surfaces and still not foam. The 12.5 cm cylinder was weighted down by a pipe so that it would roll evenly. The surface area of this arrangement was approximately 7000 cm². It was revolved at various speeds, but 16 r.p.m. was found to be optimal. Blood introduced at the upper end of the incline filmed the inner surface of the metal cylinder, the outer and inner surfaces of the screen (or plastic), and the outer surface of the pipe. An atmosphere of 95% O₂ and 5% CO₂ was maintained in the apparatus.

Results. With this apparatus an average of 22 cc of O₂ could be introduced into the blood per minute. At 250 cc per minute flow, 70 cc of blood were present in the film. Thus, a maximum of 0.406 cc of O₂ was introduced into the blood per minute per cc of blood in the film. However, foaming occurred and 10 cc of blood was lost as foam per minute.

Summary. 1. Cellulose sausage casing presents too great a barrier to the diffusion of O₂ into blood to make the Kolff apparatus an efficient oxygenator. 2. Although the Kolff machine mixes blood and oxygen, the foaming which results is excessive for an oxygenator. 3. Horizontal revolving cylinders oxygenate blood efficiently enough to make their use in animal perfusion practicable, but foaming is excessive.